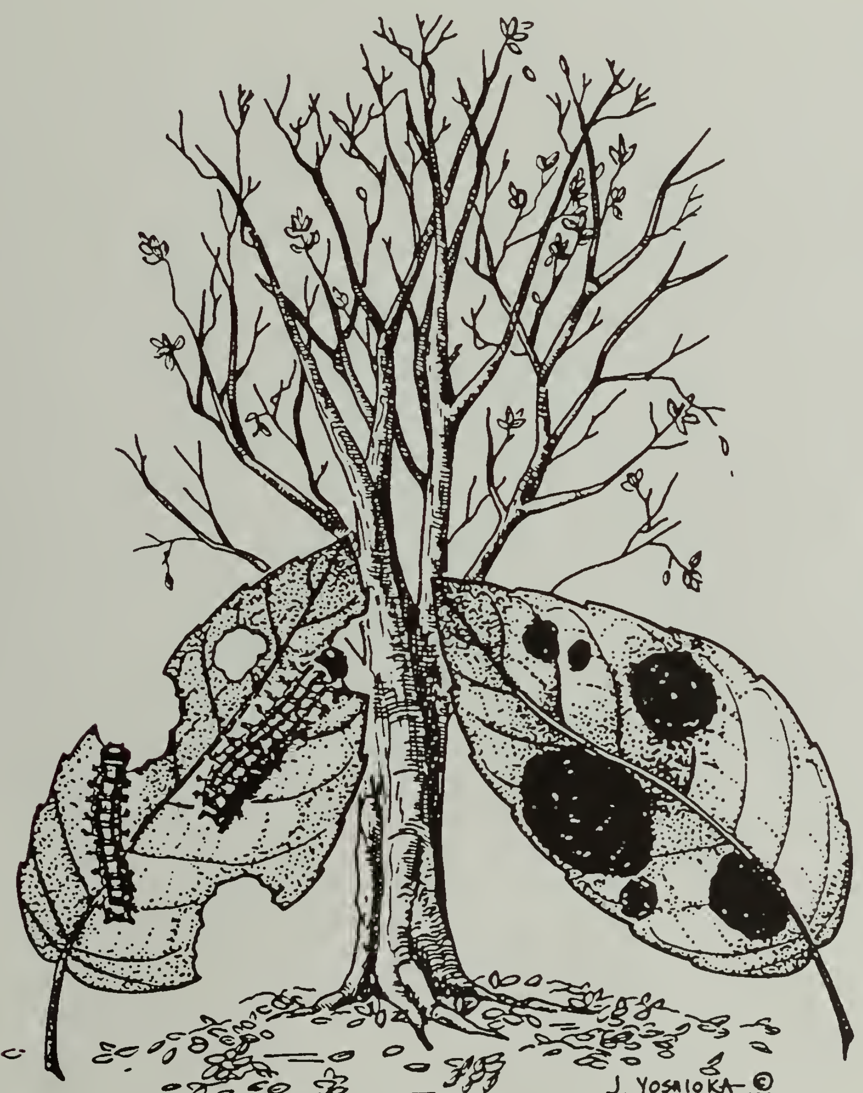
Role of Biological Control as a Management Tool in National Parks and Other Natural Areas

Donald E. Gardner

Technical Report NPS/NRUH/NRTR-90/01



United States Department of the Interior • National Park Service

The National Park Service disseminates the results of biological, physical, and social science research through the Natural Resource Technical Report Series. Natural resource inventories and monitoring activities, scientific literature reviews, bibliographies, and proceedings of technical workshops and conferences are also disseminated through this series. Documents in this series usually contain information of a preliminary nature and are prepared primarily for internal use within the National Park Service. This information is not intended for use in open literature.

National Park Service Review Notice

This report has been reviewed by the National Park Service and approved for dissemination. Approval does not signify that the contents necessarily reflect the views and policies of the National Park Service or does mention of trade names or commercial products constitute endorsement or recommendation for use.

Copies of this report are available from the following:

Publications Coordinator (FTS) 327-2156
National Park Service (303) 969-2156
Natural Resource Publications Office
c/o Air Quality Division (AIR)
P.O. Box 25287
Denver, CO 80225-0287

Role of Biological Control as a Management Tool in National Parks and Other Natural Areas

Donald E. Gardner

Cooperative Park Studies Unit, National Park Service
Department of Botany, University of Hawaii at Manoa
Honolulu, Hawaii 96822

Technical Report NPS/NRUH/NRTR-90/01

September 1990

United States Department of the Interior
National Park Service
Washington, D.C.

Contents

Figures

Acknowledgements

I gratefully acknowledge the cooperation of National Park Service regional chief scientists, and their science and resource management staffs, in supplying information from their regions. The helpful assistance of biocontrol researchers of the United States Department of Agriculture Forest Service, the United States Fish and Wildlife Service, and The Nature Conservancy is also acknowledged. I thank J. Yoshioka for the cover illustration, and J. W. Beardsley, Jr., K. Gardner, P.-Y. Lai, G. P. Markin, C. W. Smith, C. P. Stone, E. E. Trujillo, and J. T. Tunison for review of the manuscript.

Introduction

The concept of balance in nature suggests that all biological populations are under some degree of natural control exerted by competitors and environmental limitations. The science of biological control (biocontrol) may be defined as the study and use of animals (including insects) and pathogens (disease agents) to regulate host population densities (DeBach 1964). This workable definition implies the deliberate manipulation of predators and/or parasites by man to achieve desirable results. Biocontrol in some form probably has been practiced or attempted since man first noticed the controlling effects of one organism on another, such as feeding damage of insects on plants. However, the modern practice of biocontrol as generally understood was initiated and developed by economic entomologists in the late 1800s. Natural insect enemies were used for the control of unwanted species, principally in agricultural and rangeland applications. Pathogens have been more recently used for this purpose as well. The success of biocontrol efforts is largely measured in terms of economic losses prevented. Since about 700,000 of the world's more than 900,000 animals are insects (DeBach 1964) and the great majority of pest species are insects, it follows that most biocontrol applications for agricultural purposes have centered principally around control of insect pests. Use of biocontrol against weeds also has been significant, however.

Two general approaches to biocontrol of weeds with plant pathogens have been pursued: (1) the development of mycological herbicides (termed "myco-" or "bioherbicides") (TeBeest 1984) and (2) the use of disease organisms, usually from the country or region of origin of the target weed, in conventional, or "classical," programs (Templeton 1982). In actual practice, many biocontrol applications cannot be definitely categorized as either one approach or the other, but have aspects of both approaches.

Invasion by alien (exotic) species is among the most serious threats to protected natural areas. The potential of biocontrol to address this problem is often advanced by land management agencies such as the National Park Service (NPS), but these agencies have had little direct experience with this approach relative to its application in agriculture. Whereas in agriculture specific weeds or insects are targeted in an already highly manipulated environment, the integrity of the entire system is of primary concern in natural environments.

Most NPS biocontrol work to date has been conducted in cooperation with other agencies, primarily state and federal departments of agriculture, or has expanded on fundamental research by such agencies. Natural areas also may benefit indirectly from the self-distribution of agricultural biocontrol agents into these areas. However, the National Park Service has itself in recent years initiated a basic biocontrol research program with the construction of a quarantine facility in Hawaii for containment of foreign insects, and has sponsored foreign exploration for biocontrol agents.

Biocontrol requires a large initial investment, specialized research facilities, and well-trained scientists. This procedure involves international travel, interagency and intergovernmental cooperation, and communication to address conflicts of interest. This approach may not be applicable in every situation where control is desired because of conflicting management objectives or unavailability of suitable agents. However, successful programs have offered cost-effective long-range control with a minimum of apparent environmental disruption or requirement of active management, although indirect effects of introduced biocontrol agents in a native environment may be difficult to assess. Resource managers often look to biocontrol as the only feasible management approach for particularly well-established weed and insect problems over large areas.

Individual alien species may be successfully controlled in native systems; however, prospects for the overall restoration of intact, pristine systems in tropical and subtropical areas, and especially those in insular settings, are less promising. These areas are frequently under severe invasive pressure from numerous, recently arrived alien species which are available to recolonize cleared habitats. Native species, which evolved in the absence of disturbing influence on islands, are comparatively less able to compete with these influences.

History and Development of Biocontrol

The introduction of the vedalia beetle (*Rodolia cardinalis*) into California from Australia in 1888-89 for the control of cottony-cushion scale insects (*Icerya purchasi*) was the first widely recognized major success of biocontrol. California's entire citrus industry had been threatened with destruction by explosive infestations of this sap-sucking insect, but was dramatically rescued through the efforts of an exploratory entomologist who traveled to Australia, the native habitat of the scale, to search for its natural enemies.

The first modern use of insects to control weed infestations was undertaken in 1902 in Hawaii. At that time the territorial government of Hawaii authorized investigations in the native habitats (Mexico and Central America) of lantana (*Lantana camara*) for its natural enemies. Lantana is an ornamental which had escaped cultivation in Hawaii and had infested large areas of rangeland (Gardner and Davis 1982). The investigations were inspired by observations of the controlling effect that an accidentally introduced scale insect (*Orthezia insignis*) was already exerting in certain localities of lantana infestation. Over a period of several decades, a series of insects was imported both to Hawaii and later to Fiji, where substantial successful control was obtained. The introduction of insects to control Klamath weed (*Hypericum perforatum*) in 1944 was the first wide-scale effort toward biocontrol of a weed in the continental United States. Klamath weed, also known as St. Johnswort, infests large areas of the Pacific Northwest.

Other applications of biocontrol in more recent years have included the use of insect pathogens, such as the bacterium *Bacillus thuringiensis* and certain fungi (e.g., *Entomophaga* sp.) against gypsy moth (*Lymantria dispar*) and other harmful insects. Weed control with plant pathogens, particularly fungi, is also a developing field with considerable promise. The rust fungus *Puccinia chondrillina* has been used with notable success to control rush skeleton weed (*Chondrilla juncea*) on farm and rangeland of the United States and in wheat-producing regions of Australia (Cullen et al. 1973, Emge et al. 1981, Hasan 1972, Hasan and Wapshere 1973, Wapshere 1975). The rust fungus *Phragmidium violaceum* was recognized as a potential biocontrol agent of two bramble species, *Rubus constrictus* and *R. ulmifolius*, in Chile and was imported to that country from Germany for this purpose. The rust is reported to be effective in reducing the competitive vigor of the brambles (Oehrens 1977).

Trujillo (1985) introduced a pathogenic fungus, *Cercosporella* sp., from Jamaica to Hawaii in 1974 for control of the aggressive, introduced forest and rangeland weed Hamakua pamakani (*Ageratina riparia*). The fungus was later referred to as the smut fungus *Entyloma compositarum* (Trujillo et al. 1988) and described as a new species: *E. ageratinae* (Barreto and Evans 1988). The control of Hamakua pamakani has proven to be highly successful (Figures 1-4). The introduction to Hawaii of the pathogen *Colletotrichum gloeosporioides* f. sp. *clidemiae* from Panama for control of the forest weed Koster's curse (*Clidemia hirta*) (Trujillo et al. 1986) is another successful application of biocontrol against an introduced weed (E. E. Trujillo, pers. comm.).

Aquatic weed control with plant pathogens is worthy of mention here as a particularly well-defined area of biocontrol of weeds to which considerable research has been directed (Charudattan and Walker 1982, Zettler and Freeman 1972). Leaf spotting fungi and rust fungi are useful for the control of aggressive aquatic weeds, including alligatorweed (*Alternanthera philoxeroides*) and waterhyacinth (*Eichhornia azurea* and *E. crassipes*), which congest lakes and waterways in the southern United States and elsewhere.

Figure 1 An inoculation site at approximately 1,000 m elevation, with high rainfall during the summer months.

Figure 2 The same general location as Figure 1 approximately 3 years after the initial inoculation. Control was estimated at greater than 95%.

Figures 1-4 Biocontrol of Hamakua pamakani (*Ageratina riparia*) with the fungus *Entyloma ageratinae* (originally referred to as *Cercosporella* sp.) in open ohia-lehua (*Metrosideros polymorpha*) forests on the island of Hawaii. One hundred leaves at each site were inoculated with the defoliating fungus, which was subsequently widely spread by wind and rain. Data and photographs courtesy of E. E. Trujillo.

Figure 3 An inoculation site at approximately 900 m elevation with low rainfall during summer months, resulting in slower disease development.

Figure 4 Same general location as Figure 3 approximately 8 years after inoculation, with 99% control.

Note: In Figure 4, Hamakua pamakani was replaced by kikuyugrass (*Pennisetum clandestinum*).

Plant pathogenic agents other than fungi, including viruses, mycoplasma-like organisms, bacteria, and nematodes, generally have not received much consideration as potential biocontrol agents due to characteristics such as difficulty of manipulation and culturing, requirements of specific insect vectors, and lack of host-specificity. Many of these organisms are capable of producing serious diseases in crops, however, and their potential usefulness in future weed control programs should not be overlooked as biocontrol technology develops.

The mycological herbicide technique of weed control with plant pathogens was developed largely by plant pathologists in Arkansas and Florida for agricultural application, mainly in annual row crop production. This technique involves the selection of diseases which already occur on the weeds to be controlled and artificially culturing the pathogen(s) in large quantities. Masses of fungal spores are then collected, combined with an inert carrier, and sprayed or dusted on the field in much the same manner that a chemical herbicide is applied. Mass-produced inoculum of the endemic fungus *Colletotrichum gloeosporioides* f. sp. *aeschynomene* has been sprayed in Arkansas rice fields infested with northern jointvetch (*Aeschynomene virginica*) with reported control rates as high as 99% (Daniel et al. 1973, Smith et al. 1973). Weed control by this approach, as with chemical herbicides, usually requires the application of the mycoherbicide on a regular schedule each growing season. Success depends on the amplification of otherwise insignificant effects of pathogens through concentration to abnormally high levels.

If the pathogen is soil-borne, it may be incorporated into the soil prior to planting. Significant control of Texas gourd (*Cucurbita texana*) was obtained in Arkansas with the indigenous soil-borne root and collar decay fungus *Fusarium solani* f. sp. *cucurbitae* when the pathogen was incorporated into the soil prior to planting and applied to soil in pre- and post-emergence treatments (Boyette et al. 1984, Weidemann and Templeton 1988). Some mycoherbicides are sufficiently effective that they are patented, commercially produced, and marketed under trade names (Bowers 1982).

The classical approach to biocontrol with both plant pathogens and insects usually involves the initial introduction of a foreign agent into the new environment. The agent disperses itself naturally from the point(s) of introduction (Templeton 1982). Little or no attempt is made to artificially increase inoculum amounts or to apply infective material widely to target plant populations. The success of this approach is enhanced by the ability of large quantities of inoculum to survive unfavorable environmental conditions and to be efficiently self-dispersed (Shrum 1982).

Current applications of biocontrol in agriculture are numerous and relatively well-established. These approaches have been documented elsewhere (Charudattan and Walker 1982, Julien 1982, DeBach 1964, United States Department of Agriculture 1978, Wilson 1969). Historically, Hawaii has been, and continues to be, a prominent leader in biocontrol research, with an overall success rate of approximately 50% (Markin et al., in press). During the period between 1890 and 1988, a total of 681 potential biocontrol agents was successfully introduced (of an attempted number of 849) for the control of pests in Hawaii. Of this number, 254 (37%) have become established (P.-Y. Lai and G. Y. Funasaki, unpubl. rep.). A total of 38 species of insect pests and 7 species of weeds in Hawaii have been brought under complete control through biocontrol alone. An additional 13 insect species and 3 weed species have been brought under substantial control through biocontrol, which, when combined with other control methods, has rendered these pests no longer economically important (Lai 1988). The purpose of this report is to address the potential of biocontrol in the limitation of alien species in natural systems, a comparatively unexplored area, but one receiving increasing attention as widespread problems with alien plants increase. Markin and Yoshioka (in press), Markin et al. (in press), and Gardner (in press) have discussed biocontrol principally as it applies to native ecosystems in Hawaii.

Suitability and Application of Biocontrol in Natural Settings

Invasion and disruption of natural habitats by alien species are among the most serious threats to the integrity of many of these areas. Official NPS policy provides for the control, and elimination where possible, of alien species and specifies biocontrol as an acceptable approach for this purpose. A 1981 memorandum from NPS Director Russell Dickenson (ref. N50(496)) updating the 1978 NPS *Management Policies* handbook states:

> Chemical pesticides of any type will be used only where feasible alternatives are not available or acceptable. The Service's use of all pesticides shall be approved by the Director. Application shall be in accordance with applicable laws, Departmental and Service guidelines, and Environmental Protection Agency and Occupational Health and Safety Administration regulations.
>
> Service policy does not prohibit, as such, the use of chemical pesticides. However, chemical controls are to be allowed only if (a) there is a clear and present danger to the health and safety of man; and/or (b) there is danger of destruction of significant property or resources and a determination has been made that the control methods of no action, mechanical, cultural and/or biological control are non-existent, unavailable, or unacceptable.

The 1985 Guide for Pesticide Use in the National Park System specifies the following priorities:

> After the pest is correctly identified, an analysis of the following control methods should be carried out: (1) no action, (2) mechanical and cultural control, and (3) biological control....
>
> If the above control methods...are non-existent, unavailable, or unacceptable, a chemical control method may be considered.

The stated preference for biocontrol approaches over use of chemical pesticides is idealistic at this time because relatively little actual precedent exists for the application of biocontrol techniques in natural environments. In actual practice, NPS resource managers have access, for the most part, to neither the funding resources, the scientific expertise, nor the specialized equipment and facilities necessary to explore thoroughly biocontrol possibilities prior to the use of conventional methods. Furthermore, when the disruptive nature of an alien species becomes evident, resource managers usually prefer to proceed as rapidly as possible with direct control. The NPS objective in controlling alien plants for the preservation of native ecosystems differs in some respects quite markedly from that of agriculture, including horticulture or range management. The goal of agricultural biocontrol programs is focused on the preservation of a specific crop or forage type in the already severely manipulated environment of cultivation. The success of such programs is measured primarily in terms of economic losses prevented. The objective of the National Park Service, in contrast, is to maintain, as nearly as possible, the overall integrity of the native system itself as an intact entity. Such a holistic consideration, in which the measure of success may be more of an aesthetic and functional than economic nature, is expressed in the same abstract terms of environmental quality and intrinsic societal value with which the National Park System itself is largely characterized. Simply expressed, the more a natural area is manipulated by managers, the less natural it becomes.

Integrated pest management (IPM) is a practice of increasing popularity in agricultural settings. Depending on specific requirements, this concept combines cultural practices, such as favorable timing of soil cultivation, irrigation, fertilizer application, and the planting of resistant varieties, with biocontrol, and the judicious use of chemical pesticides to bring about the desired pest control. IPM principles are receiving increasing attention in the management of historic and recreational National Park System sites where the exclusive use of chemical pesticides is not desirable. However, the IPM components that require extensive environmental manipulation are not compatible with the management of natural environments; applicability of these approaches is greatly reduced in these areas.

Difficulties with the concept of biocontrol in natural settings have led to some expressions of opposition to this approach. According to these views, greater concern for the potential indirect, as well as the direct, effects of an introduced biocontrol agent in native environments, as contrasted with agricultural settings, is called for. Nevertheless, assessing fully such indirect ramifications may not be possible (i.e., competition with native species, unbalancing of food webs) prior to release. For this reason, the concept of biocontrol in natural environments is not universally accepted. "Biological pollution" may result from introductions that prove to be of little value in controlling the target species, but which themselves become established in the system (Howarth 1983). Screening requirements have been increased and enforced in Hawaii, where, as mentioned previously, biocontrol work has been actively underway since the late 1800s, and the incidence of indiscriminate, unproven introductions has been sharply decreased (Funasaki et al. 1988). Notwithstanding this, the deliberate introduction of any alien organism with the intent that it become permanently established in a natural system, regardless of the intended beneficial purpose, is not acceptable to some. This is particularly true since the target organism is rarely eradicated by the agent, resulting in the presence of two (or more) alien organisms where only one was originally present.

The current unavailability of accessible certified quarantine facilities, supported by trained biocontrol researchers, is probably the most serious practical impediment to the use of biocontrol approaches in most parks and other natural areas throughout the United States. Inspection and certification of containment facilities for foreign organisms is under the jurisdiction of the United States Department of Agriculture Animal and Plant Health Inspection Service (USDA-APHIS) and the department of agriculture of the state where the facility is located. Whereas specifications for such structures, particularly those designed to contain microscopic organisms (pathogens), have been flexible and quite arbitrary in the past, more rigorous regulation, and construction requirements, have been imposed in recent years. Experience has shown that facilities that received tacit approval for biocontrol work in the past are no longer adequate.

Ryan (1987), in discussing entomological biocontrol research in the USDA Forest Service, stated:

> Importation of exotic natural enemies is beyond the competence not only of foresters but also of most entomologists.... Because of strict quarantine requirements, importing natural enemies requires an entomologist skilled in ecological theory, insect taxonomy, parasite and predator biology, and handling methods. That combination of skills is rare even among professional entomologists.

Ryan's concern for entomologists is equally true of plant pathologists trained to conduct biocontrol research. Biocontrol programs must be directed by fully professional, competent scientists. Likewise, biological technicians, and other support personnel, must be qualified to handle potentially destructive agents, which, if inadvertently or prematurely released, are often irretrievable. All personnel involved with biocontrol work must have both the proper technical training and a proper attitude and understanding of the critical nature of the programs.

As alluded to previously, initial costs involved with biocontrol can be of such magnitude as to appear prohibitive, particularly since these costs would most likely involve construction of a quarantine facility. As mentioned, little precedent is available for such structures, but total construction costs for the small Hawaii State Department of Agriculture (HDOA) quarantine facility for foreign plant pathogens have been unofficially estimated to exceed $1 million. Some of these expenses were incurred by the necessity of making major revisions to correct inadequacies that became evident during the initial inspection.

Notwithstanding these constraints, a general optimism for biocontrol approaches as a solution to some of the most pervasive pest problems persists. Ryan (1987) stated:

> In many cases, foresters have ignored biological control, one of our most effective techniques for controlling insects.... The only states with major efforts in importation work, California and Hawaii, recorded 84.2% of the successes in the U. S., compared with only 15.8% for the rest of the states and the USDA combined.... Some pests will naturally be more amenable than others to control by introduced enemies. Success or failure cannot be predicted, but not trying will guarantee failure.

The USDA Forest Service has targeted several insect species as high priority pests against which biocontrol efforts are directed. Among these are the gypsy moth, the spruce budworm (*Choristoneura fumiferana*), the western spruce budworm (*C. occidentalis*), the larch casebearer (*Coleophora laricella*), and species of the tussock moth (*Orgyia* spp.). Aerial spraying of infested forests with biological "insecticide" which has *Bacillus thuringiensis* as the active ingredient, or with insect-infecting virus preparations, as well as introduction of parasitizing insects, have proven effective in controlling several of these pests (Ryan 1987, Ryan et al. 1987, Torgersen and Torgersen 1990).

The use of virus diseases against gypsy and tussock moths is an innovative approach worthy of particular attention (Torgersen and Torgersen 1990). Since virus particles are submicroscopic and therefore not identifiable through normal observation, infected larvae (caterpillars) themselves were collected and allowed to decay in water. The insect tissue was then separated by centrifugation and filtration from the liquid, which contained the virus. Healthy larvae treated with the virus-containing liquid contracted the disease. Although not all viruses are as easily transmitted, the "holistic" approach used here proved effective. Eventually a commercial formulation of the gypsy moth nucleopolyhedrosis virus resulted from this work, and was registered as a bioinsecticide under the trade name Gypchek®.

Through a cooperative agreement between the United States Departments of the Interior and of Agriculture, the USDA Forest Service Forest Pest Management Unit has applied biocontrol techniques to the management of gypsy moth infestations in forests administered by the NPS National Capital Region (Reardon and Carothers 1988). Commercial formulations of *B. thuringiensis* as well as Gypchek are applied using aerial or ground application methods. According to Reardon and Carothers (1988), "The natural enemy complex (parasites, predators, and disease) have not yet been shown to be effective control factors when gypsy moth populations are moderate to high; however, they may be important factors at low densities." Applications of the female gypsy moth sex attractant pheromone disparlure, commercially known as Luretape-GM® is also a treatment available for trial. Similar efforts against gypsy moth have been pursued by scientists and managers in other Atlantic National Park System areas with considerable success.

Current and Potential National Park Service Involvement in Biocontrol Work

Due largely to the high initial costs involved, and to the fact that the National Park System has neither a large research staff nor an official research function, most of the biocontrol investigation and application undertaken on behalf of the National Park Service are conducted as cooperative efforts with other agencies. Agencies include the USDA Forest Service, the USDA-Agricultural Research Service (USDA-ARS), state departments of agriculture, or state university faculty. Where formal cooperative agreements have been absent, most biocontrol work conducted by the National Park Service has heretofore expanded on fundamental research initiated by other agencies. Natural areas probably also benefit significantly from self-distribution of biocontrol agents from agricultural lands in keeping potential problem aliens in check. Such on-going effects may continue largely unnoticed since they do not demand the attention of resource managers.

Several such "secondary" biocontrol efforts, in which NPS managers or scientists have taken advantage of biocontrol programs initiated by other agencies both in National Park System and in non-park areas, have been applied to NPS needs with encouraging results. An example is the control of tansy ragwort (*Senecio jacobaea*) with the tansy flea beetle (*Longitarsus jacobaeae*) at Redwood National Park (Holden 1985). Foreign exploration for potential control agents in the native habitat of tansy ragwort (The Netherlands), export to the United States and testing under quarantine, and release of insects in the field were carried out by USDA scientists. Introducing and monitoring the establishment and activities of biocontrol insects in tansy ragwort-infested areas of Redwood National Park were a cooperative effort among the United States Department of Agriculture, the local county farm advisor, and the resource management staff at Redwood.

Parks of the Pacific Northwest Region (PNR) are the beneficiaries of biocontrol research conducted by an entomologist at Washington State University, who is investigating biocontrol of diffuse knapweed (*Centaurea diffusa*), spotted knapweed (*C. maculosa*), Canada thistle (*Cirsium arvense*), Klamath weed, and poison hemlock (*Conium maculatum*). Managers have listed a number of other potential target weeds for biocontrol in PNR parks (Piper 1985; M. J. Tollefson, pers. comm.).

A further successful application of biocontrol in natural areas by NPS managers and scientists, in cooperation with the California Department of Food and Agriculture, is the release of beetles (*Chrysolina quadrigemina*) in Yosemite National Park for the control of Klamath weed (Anon. 1981). The use of *Chrysolina* beetles as biocontrol agents for extensive infestations of Klamath weed throughout Northern California and the Pacific Northwest is a well-known example of a successful biocontrol program (van den Bosh et al. 1982). Since the appearance of this weed in Yosemite in the 1940s, attempts at hand eradication and herbicide spraying have been ineffective. *Chrysolina* beetles were originally released in 1951 in Yosemite, and within 10 years Klamath weed was nearly eliminated from the park. A subsequent decline of the beetle population enabled a more recent reinvasion by the weed, but reintroduction of *C. quadrigemina*, with the possible use of two other known Klamath weed insects, if necessary, resulted in optimism about control of the weed.

USDA entomologists are conducting biocontrol investigations of the broad-leaved paperbark tree (*Melaleuca quinquenervia*), with initial funding provided by the National Park Service and the United States Army Corps of Engineers in Florida (Balciunas and Center 1989). Paperbark is an aggressive invader from Australia recognized by the National Park Service, as well as other land-

managing agencies with economic interests in southern Florida, as a destructive, highly undesirable species. Work still underway has included exploration in Australia by USDA scientists for potential controlling agents and evaluation of candidates for suitability for release in Florida.

An innovative biocontrol research approach by NPS scientists in the National Capital Region is worthy of mention even though not applicable strictly to natural environments and apparently less successful than desirable (Sherald and Hammerschlag 1982; J. L. Sherald, pers. comm.). American elm trees (*Ulmus americana*) of high individual aesthetic value, but infected with Dutch elm disease, were injected with isolates of the bacterium *Pseudomonas syringae* known to be antagonistic in laboratory cultures to the pathogenic fungus *Ceratocystis ulmi*, the causative agent of the devastating disease. Unfortunately, the inhibitory effects of the bacterium against the fungus were not evident in diseased trees.

Another application of a biocontrol approach by NPS managers, although again not in a park managed primarily for preservation of natural systems, was the use of a grasshopper bait treated with spores of the pathogenic protozoan *Nosema locustae*. The bait was broadcast from aircraft and successfully controlled excessive infestations of those insects at Golden Spike National Historic Site (Wagner 1986). Although a decline in grasshopper populations was evidently more gradual than with treatment with chemical insecticides, the protozoan is specific to grasshoppers and is transmitted with the eggs to the following generation. Thus, environmental contamination or unwanted side effects sometimes associated with chemical pesticides were avoided; the biological qualities of the controlling organism enhanced the efficiency of this treatment method. Feasibility of a similar approach in natural sites would depend largely on possible effects of bioinsecticide on native insects.

As mentioned, invasions by alien plants are widely recognized as being among the most pervasive threats to natural systems. National parks and similar natural preserves in warmer regions, such as Everglades National Park, and those in the Virgin Islands and Hawaii, are severely impacted by such invasions.[1] The only practical solution to many of these problems, if indeed solutions are to be found, appear to involve biocontrol (Doren 1989, Gardner 1982).

Until recent years, as was discussed earlier, the National Park Service had not engaged in such primary biocontrol activities as foreign exploration, host range testing under quarantine or in the native country, and initial introduction of agent(s) to the United States. However, the urgency of Hawaii's alien plant problem led to construction by the National Park Service of a quarantine facility in Hawaii Volcanoes National Park (Gardner and Smith 1985). The facility was certified by the Hawaii State Department of Agriculture and the United States Department of Agriculture-Animal and Plant Health Inspection Service to contain foreign insects (but not plant pathogens) for biocontrol research. Under a cooperative agreement among the USDA Forest Service, the Hawaii State Department of Agriculture, the state of Hawaii Department of Land and Natural Resources, the

1. As a note of interest, both Everglades and parks in Hawaii share *Schinus terebinthifolius* as one of the most seriously disruptive alien species in each region, although these areas are widely separated from one another geographically. The common name of the tree in the Everglades is Brazilian peppertree (or Brazilian holly), whereas this species is known as Christmasberry in Hawaii, illustrating the confusion that can result from use of common names.

University of Hawaii, and the National Park Service, the facility is staffed by a USDA Forest Service entomologist. Construction of this facility, as well as approval of foreign travel by an NPS plant pathologist for the purpose of biocontrol exploration (Hodges and Gardner 1985, Gardner et al. 1988), indicate the growing involvement of the National Park Service and the United States Department of the Interior in biocontrol research.

Whereas the alien species most frequently identified as candidates for biocontrol in National Park System areas are weeds rather than insects or other microfauna, insect-related problems are not to be minimized, as illustrated by the gypsy moth invasion of eastern forests. The Argentine ant (*Iridomyrmex humilis*), and the alien ground-nesting yellowjacket wasp (*Paravespula pensylvanica*) in Hawaii, prey on native species including endemic pollinators, and, in the case of the yellowjacket, are threats to human health and safety (Gambino et al. 1987, Loope et al. 1988). As greater awareness of interactions among native insects and other microfauna and alien species is gained, control of these sometimes less conspicuous invaders may become a problem of higher priority than it is now often perceived to be.

Biocontrol Procedures

Upon determination that a biocontrol approach is necessary or desirable, assessing the extent to which the weed or other target organism is already being impacted by insects and pathogens in the new environment is important. If enhancement of control by agents already occurring in the system is possible, much time and effort may be saved. Furthermore, it is not desirable to introduce agents that may have a competitive or inhibitory effect on already functional agents if this can be avoided. The Hawaii State Department of Agriculture exercises the precaution in its current biocontrol program that insects purposefully released have been exhaustively evaluated for possible negative effects. However, earlier indiscriminate releases or occurrence of immigrant parasites (i.e., unintentional arrivals) of various economically important moths in Hawaii during the early 1900s have been considered responsible for the near extermination of many native Hawaiian Lepidoptera (Zimmerman 1958). Biological pollution now threatens the establishment of Lepidopteran agents for the control of weed species, such as is currently being attempted with the South American moth *Cyanotricha necyria* imported to Hawaii for control of the banana poka vine (*Passiflora mollissima* or *P. tripartita*), a serious weed in Hawaii Volcanoes National Park and other native forest areas (Markin and Nagata 1989) (Figures 5-6).

As might be expected, the conventional approach to biocontrol, as discussed in the History and Development of Biocontrol section, rather than the use of mycoherbicides, usually is somewhat more applicable in natural areas or other nonagricultural situations. In these locations, weeds are often widely scattered over difficult terrain and access for treatment on an individual basis is limited. Even in natural areas, however, certain alien grasses and woody species may become established in monoculture-like stands, to the exclusion of native vegetation. In these situations mycoherbicide-type techniques may bear consideration.

The fact that the alien species has been identified as a problem requiring biocontrol indicates that locally occurring agents, if present, are not effective in most cases. Although troublesome weeds targeted for biocontrol in agricultural programs are sometimes native species, the invasive plants considered for biocontrol in natural systems have been, with few exceptions, introduced from other parts of the United States or from foreign countries.

Notwithstanding the previous generality concerning the ineffectiveness of local agents, the biocontrol program against prickly pear cactus, also known as tree cactus (*Opuntia megacantha*), in Hawaii is a notable example of the successful application of a fungal disease agent already present in the environment (Carpenter 1944). A locally obtained variety of the pathogenic fungus *Fusarium oxysporum*, a soft rot-causing organism, was used as the pathogen. Workers manually inoculated the plants by creating wounds in the cladodes (pads) into which small portions of fungal cultures were introduced. This approach, which was particularly well-suited to the growth habit and distribution of prickly pear on Hawaiian ranges, may perhaps be considered a hybrid biocontrol technique since it involved elements of both the mycoherbicidal and the conventional concepts, i.e., a naturally occurring pathogen was cultured and its success in distribution and infection was greatly enhanced through artificial manipulation. However, the pathogen was not produced in large quantities for widespread, blanket application. Similar approaches may have some application in National Park System areas where target alien plants are individually distributed and readily accessible (e.g., among well-spaced trees or shrubs), and where personnel requirements would not be prohibitive.

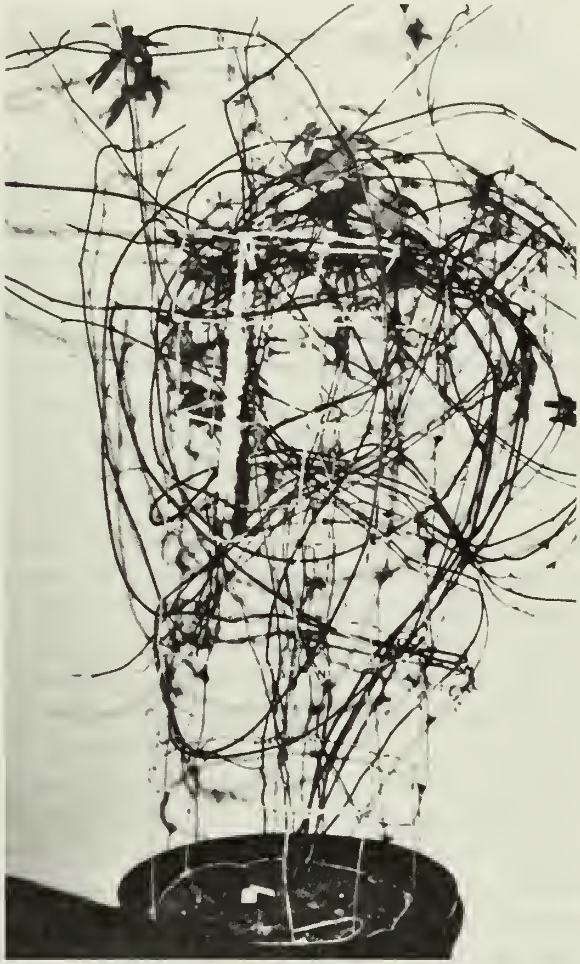


Figure 5 Defoliated banana poka after 30 days feeding by 100 insect larvae.

Figures 5-6 Promising feeding trials of the moth *Cyanotricha necyria* in the Hawaii Volcanoes National Park insect quarantine facility. Courtesy of G.P. Markin.

Figure 6 An unaffected commercial passion-fruit plant similarly exposed to 100 larvae for 30 days.

The cactus biocontrol program was later supplemented with several imported species of insects (Fullaway 1954). Among the insects used, *Cactoblastis cactorum*, a moth native to Uruguay, which had proved highly successful in controlling cactus in Australia, was credited as one of the most important insect agents in controlling the Hawaiian infestation (Fullaway 1954) (Figures 7-10). The usefulness of *C. cactorum*, which typically deposits its eggs on cactus spines, in controlling the spineless type of prickly pear occurring in Hawaii Volcanoes National Park is currently under investigation (Davis et al., in press).

A second example, also from Hawaii, of opportunistic use of a pathogenic fungus already occurring in the environment for biocontrol, is for the escaped ornamental leguminous tree kolomona (*Cassia surattensis*), which had become a pest on ranchland (Trujillo and Obrero 1976). A severe wilt-causing isolate of *Cephalosporium* sp. was recovered from diseased kolomona tissue on the island of Kauai. The fungus was grown in artificial culture and determined to be host-specific in greenhouse inoculation tests of other species of *Cassia*, as well as *Leucaena leucocephala* (=*L. glauca*), another weedy, introduced leguminous tree. Trees in the field were inoculated by spraying a spore suspension into cuts made in the stem, exposing the xylem tissue. Fewer than 5% of the total number of trees present were inoculated. All inoculated trees died within 4 months, and the pathogen spread by natural means from the inoculated trees throughout the population, such that at the end of 1 year, 100% mortality was obtained on a dry site of approximately 4 acres (1.7 hectares). Control was somewhat lower at sites where more rainfall occurred, but even in these areas trees that did not die showed evidence of infection. After 3 years, kolomona had been reduced from 80% infestation to less than 1% on more than 30 acres (12.5 hectares) of pasture land.

Prior to initiation of a biocontrol program, a thorough review of the scientific literature for references to diseases and insects of the target weeds, and related species elsewhere, is necessary. The fact that aggressive alien organisms are rarely considered a problem in their native habitat suggests, at least in part, that the activity of natural enemies in the native habitat maintain the species population in balance. Experience has shown, however, that unless a target plant is of economic importance in its native habitat, it probably has received little research attention there. This is particularly true if the native region is a foreign country with limited scientific resources. Few entomologists or phytopathologists are available in developing countries to devote attention to research projects unless they are of high priority to the agriculture of those regions. The pathogen flora or insect fauna associated with the target species, or its relatives, may be therefore not well documented in the scientific literature. A firsthand search in the native country may be necessary for an accurate assessment of potential biocontrol agents (Charudattan 1982, Zwoelfer et al. 1976).

Experience has proven that assistance offered by local government, scientific, forestry, university, and similar personnel is perhaps the most valuable single factor in facilitating exploratory efforts for biocontrol agents in foreign countries and assuring success. Many foreign scientists, while not able to devote actual research attention to priorities other than their own, are motivated by curiosity, often a great deal of generosity, and an eagerness to establish professional relationships with American scientists who share their interests. These personnel may provide specific information and direction to locations of populations of the target species; they may even personally accompany exploratory scientists to sites, saving a great deal of time and frustration, particularly in countries with languages unfamiliar to the visitor. Accompaniment by someone with knowledge of the local culture and language may also help gain access to areas such as private land, which would otherwise be inaccessible to foreign visitors. It is useful for both local and visiting personnel to cultivate cooperative relationships. Visiting personnel should take care that the local cultures and customs are respected. Provisions for grants-in-aid to collaborators in less technologically developed countries are always appreciated and can be very productive.

Figure 7 Infestation at the time of release in 1950.

Figure 8 The site in 1954.

Figures 7-10 Biocontrol of prickly pear cactus (*Opuntia megacantha*) with the moth *Cactoblastis cactorum* and other insects on the island of Hawaii. Photographs courtesy of the Hawaii Department of Agriculture.

Figure 9 The site in 1958.

Figure 10 Complete control in 1962.

Note: In Figure 10, the appearance of fountaingrass (*Pennisetum setaceum*), an invasive bunchgrass currently posing a serious threat to drier regions of Hawaii Volcanoes National Park.

Observation of potential biocontrol agents in their native environments allows one to assemble information on host ranges, life cycles, fruiting habits, distribution, abundance, and destructive impact on the host. Likewise, information on the host itself as it occurs in its native habitat can be gathered for comparison with ranges and growth habitat in the region to which it has been introduced. These data are useful, but caution should be exercised in attempting to assess the effect of the agent in the new area by its effect in the original habitat. The biocontrol organism, like the host plant itself, may behave differently in the new environment than in the native habitat. Among insects in particular, predation or parasitism by other insects or disease agents may mitigate the effect of the insect in the native habitat as compared with that in the new environment which is free of these limiting factors. Care should be exercised, therefore, that collections not be accompanied by natural predators or parasites before transporting or releasing insects into the new environment. Although hyperparasitism among fungi is known, activity of fungal pathogens in native habitats may be in general considered more nearly an indication of their potential effectiveness in the new environment, than is the case with insects. That is, parasitism does not usually play a major role in limiting the virulence of fungi, although certain fungi, such as *Sphaerellopsis* (=*Darluca*) *filum*, a universally distributed hyperparasite of rust fungi, may exert a significant impact on this group of obligate plant pathogens.

Ideally, exploratory trips to a given area should be conducted during different seasons to provide the greatest opportunity for observation of potential biocontrol agents and their effects. Initial evaluation and screening of a potential agent is sometimes best conducted in the native country before importation into the United States (Charudattan 1982). When this is not possible, agents to be tested under quarantine (those not already present in the United States, or, depending on state regulations, in the state into which the agent is to be introduced) should be transported as expediently as possible to ensure the greatest chance of survival.

It is disheartening to the exploratory researcher to have expended considerable time and energy in collecting agents in a foreign country, only to have the perishable collections unduly delayed by bureaucratic "red tape," or to have them prevented from leaving the home country altogether. Such complications are not uncommon in certain foreign countries despite efforts to anticipate official requirements beforehand. Preestablished contact with influential local officials, who are kept informed of exploratory activities, may be helpful in assuring the expeditious processing of collected material at the time of departure.

Biocontrol agents collected in a foreign country, particularly insects and obligate parasitic fungi (i.e., those that cannot be cultured on artificial growth medium), are usually under stress and vulnerable to unfavorable environmental conditions while in transit. They should be transported as rapidly and as efficiently as possible to quarantine in the United States. Insects are often best transported in the pupal (a dormant) stage, when possible, to avoid the necessity of maintaining a fresh supply of food to active colonies. Insects or pathogens must not be exposed to unduly high or low temperatures, or to drying conditions during transportation, such as may be encountered in baggage compartments of airplanes, or exposed to the sun in an enclosed container. As mentioned earlier in the Biocontrol Procedures section, hand carrying is probably the best method of insuring proper care of agents during transportation.

The researcher frequently finds it necessary to alter an original itinerary after arrival in the country of destination, and to make "on the spot" decisions as to the most expeditious use of time and travel funds, depending on local weather conditions, phenology of the agent(s) or host, and similar unpredictable factors. A stay in a foreign country may be extended if the researcher encounters unexpected delays, or if new leads become apparent. Use of laboratory facilities, supplies, equipment, and other needs at a local research establishment may be desirable, or contract funding for local scientists and assistants, if available, may be necessary to conduct or support the work.

USDA-APHIS regulations, and those of individual state departments of agriculture, require that foreign insects and plant pathogens be imported for study purposes under a permit. Permit issuance is greatly facilitated by information on the biology and host range of the organism in the original environment. The organism should be fully identified prior to importation. However, if the insect or pathogen appears to represent a new species, it may, on a case-by-case basis, be admitted to the United States pending further study under quarantine.

A serious complication, pertinent to this discussion, currently affecting importation of lepidopterous agents from Colombia to the HAVO quarantine facility for control of banana poka (Markin and Nagata 1989) is the threat of accidental importation of protozoan parasites referred to as microsporidia. These microscopic organisms may be present in wild insect populations and become inadvertently introduced with their hosts to the quarantine facility. If the facility has, in fact, become contaminated with microsporidia, it may be necessary to destroy all insects, purge the facility, and reinitiate studies with insects known to be free of the parasite. Microsporidium-infested insects must not be released into the environment, where the parasites could become permanently established in biocontrol insect populations, destroying their effectiveness. Sampling procedures have been developed to detect presence of microsporidia in insect populations, but it is safer to rear two or more generations in the laboratory in the native country, carefully observing each generation for evidence of microsporidium disease.

Requirements specify that all potential biocontrol agents of foreign origin must be maintained in a certified quarantine facility to prevent premature escape for host range and similar studies (Klingman and Coulson 1983). Since pathogenic fungi and other plant disease agents are microscopic, or produce microscopic spores that are often air-borne, specifications for quarantine facilities in which pathogens are to be contained are more stringent than are those for facilities in which insects are maintained (Melching et al. 1983, Gardner and Smith 1985).

The United States Department of Agriculture-Agricultural Research Service operates a limited number of certified containment facilities for entomological biocontrol research throughout the United States; the previously described HAVO insect quarantine laboratory is the only such facility currently operated by the National Park Service, and possibly by any agency not primarily engaged in agricultural research.

The HAVO laboratory was constructed from an existing 31 x 22 ft. (9.4 x 6.7 m) conventional greenhouse section (Gardner and Smith 1985). Among other modifications, glass siding was replaced by transparent Lexan Margard® polycarbonate to ensure resistance to breakage. Ventilation and temperature control are provided by the movement of copious volumes of ambient air through the structure with large fans. The air is filtered by double layers of fine-mesh (100) stainless steel screens. Foreign insects under investigation are confined to cages or growth chambers within the laboratory where they are maintained on specified plant material to test their feeding and reproductive ability. All joints and seams throughout the laboratory are sealed to eliminate possible escape routes for insects that may escape internal confinement. The structure is isolated by a water-filled moat, and is otherwise free of contact with other structures, to discourage crawling insects from entering or leaving. The laboratory is entered through two small, black-painted entry rooms, each furnished with a light trap, designed to attract any escaping insects. Three solid, air-tight, walk-in refrigerator-type doors separate the entry rooms. A safety mechanism prevents both outside and inside doors from being opened simultaneously. Laboratory workers are required to wear laboratory coats, which are removed and left in the entry room upon exiting the facility. Access to the laboratory is strictly limited to the small number of predesignated researchers and technicians who are directly involved with the project, and who are familiar with security procedures and the insects being maintained in quarantine.

The facility is provided with a large autoclave mounted through the wall with doors both inside and outside the secured area. All potentially contaminated biological materials to be discarded must pass through the autoclave. Many of the design and labor services were donated by the Pacific Area Office of the National Park Service and by Hawaii Volcanoes National Park's Division of Maintenance; however, the Denver Service Center fee for design consultation was $5,000. Cost of actual construction, exclusive of donated labor, was approximately $73,000. The specialized autoclave cost an additional $34,000 (purchased in 1983, including an 18% General Services Administration discount). Current average monthly operating costs, mostly for electricity, are approximately $600. The facility must be inspected on a regular basis and maintained in good condition such that deterioration of the screens, leaks, malfunctioning of fans and other equipment, etc., are promptly corrected. Electrical outages may result in rapid temperature increase within the laboratory, which could destroy the insect colonies. A backup, gasoline-operated generator is available to begin immediate operation in the event of a power failure.

Operating containment facilities certified for work with foreign plant pathogens (as distinct from insects) are in short supply nationwide (Charudattan 1982, Melching et al. 1983). The only such facility currently available in the United States, which is adequate for general host range testing of foreign pathogenic fungi, is the USDA-ARS Foreign Disease - Weed Science Research Unit, at Ft. Detrick, Frederick, Maryland. Even this laboratory, however, has limited space relative to the many priority weed biocontrol projects being conducted nationwide. The directorship of the laboratory must regulate research activities so as not to overburden these facilities. A full description of this laboratory has been published (Melching et al. 1983).

Kahn (1983) published a comprehensive discussion of the proper design and maintenance of quarantine facilities for all types of biocontrol programs. Foreign plant pathogen containment requirements are of necessity stringent, and include a negative air pressure system, an air filtering system capable of removing submicron-sized particles, waste water containment and treatment provisions, self-contained air conditioning, double-doored autoclave, and sealing safety doors, among other safeguards. Emergency equipment, including a self-sufficient power generator, must be available in case of power failure. Insect containment facilities, while also stringent in their design requirements, may be constructed without the same air-tight, negative pressure and air filtering system necessary to remove microscopic particulate matter (i.e., spores) from the expelled air.

The Phytotron at Duke University in North Carolina, while not used strictly as a containment facility for foreign pathogens, is a self-contained environmentally controlled structure with many of the specifications of a quarantine laboratory. A recently compiled cost analysis for Duke's Phytotron therefore may be applicable to this discussion (C. W. Smith and D. E. Gardner; unpubl. rep., files of NPS, Western Region, San Francisco) (Appendix A).

A containment facility on this scale, if operated by the National Park Service, would presumably be centrally located and capable of serving the biocontrol research needs of one or more regions. However, in isolated, tropical areas such as Hawaii, where invasion by alien species is severe and the problems are not shared by mainland parks, separate facilities may be warranted.

As previously mentioned, the Hawaii Department of Agriculture is constructing a small biocontrol facility for the containment of foreign plant pathogens. Due to site limitations at the Honolulu location and the high cost of construction, research at the facility will be restricted primarily to projects of highest priority to Hawaiian agriculture. Some National Park Service cooperative research is possible, but the facility is located near sea level where most agricultural weeds occur and may not be capable of simulating the temperatures of higher elevations where many currently invasive forest weeds occur. The usefulness of this facility to NPS needs therefore may be limited, although the Hawaii Department of Agriculture has expressed its desire to cooperate with the National Park Service to the extent possible.

Factors to Consider in Biocontrol Programs

Expectations of Biocontrol

Some potentially negative aspects of biocontrol may lie in the expectations of resource managers, and their perception of what successful control entails. An important characteristic of biocontrol programs is the considerable time their successful completion often requires. The necessary patience may detract from park managers' satisfaction of witnessing the occurrence of decisive results within their own tenure in a particular park. Even after an agent has been imported into quarantine, testing may require several years.

Inherent in this lengthy procedure is the understanding that exploration and testing are undertaken with no guarantee of success. That is, suitable agents may not be located, may not exist at all for a particular target species, or prove unsatisfactory during testing.[2] Markin and Yoshioka (in press) provided a checklist of critical factors relating to biocontrol programs whereby the potential of implementing a successful program for each target species on an individual basis may be evaluated.

While most plant species have several types of insects and disease organisms associated with them, successful biocontrol candidates must meet two basic criteria: (1) The agent must be host specific or of such limited host range that nontarget species are not endangered. Biocontrol programs for natural systems must particularly consider potential effects on native species as well as the crops and ornamental plants of the region. Consideration of native species and ecosystems is frequently minimized in agricultural biocontrol programs. (2) The agent must be sufficiently virulent to impose a significant subduing impact on populations of the target species. Most insects or pathogens may cause minor damage, as by limited foliar feeding or production of a few leaf spots, but these effects exert little influence on the health of the host itself. Insects or pathogens capable of actually limiting populations of aggressive, rapidly colonizing target organisms are exceptional. As mentioned earlier, however, insects mitigated in their effects by predation or parasitism in their native habitats may prove to be effective biocontrol agents when released from these pressures in their new locality. Conversely, the new environment may provide limiting factors to newly released insects not encountered previously. The moth from Colombia, *Cyanotricha necyria*, discussed previously in conjunction with biocontrol of banana poka in Hawaii, shows in quarantine both of the desired qualities of host specificity and ability to attack the target species severely (Markin and Nagata 1989) (Figures 5-6). However, field releases of *C. necyria*, based on the success of this insect in quarantine, have not yet shown successful establishment of the agent in nature, possibly due to predation by other insects (G. P. Markin, pers. comm.).

2. Conventional control measures should not be suspended prematurely while biocontrols are being developed. Firetree, or fayatree (*Myrica faya*), a well-established alien species in Hawaii Volcanoes National Park, for which approximately $400,000 has been expended on control during the past 15 years, was considered beyond control in the early 1980s. However, in the absence of effective biocontrols to date, a system of representative habitats, designated special ecological areas (SEAs) was developed (Tunison et al. 1986; Tunison and Stone, in press). that has yielded promising results. Hand removal of fayatree, and a number of other troublesome alien plants, from these areas appears cost-effective and requires diminishing effort, enabling gradual expansion of the SEAs.

The activity of biocontrol agents also may be influenced by "microenvironments." Rust (*Phakopsora apoda*) of kikuyugrass (*Pennisetum clandestinum*) can cause severe infection under shady conditions, but its effects are mild in full sunlight only a few meters away (Gardner 1984). Similarly, agents may prefer wetter or drier conditions or be more effective at particular elevations than at others (C. J. Davis, pers. comm.).

Once released into the new environment, biocontrol agents must have time to increase in population and become distributed throughout the range of the target species. If seasonal cycles with periods of inactivity are involved (e.g., during winter), the effects of the agent may develop subtly over a period of several years and populations of both the agent and the target species may fluctuate from year to year. Initially, reductions of target populations may be apparent only when observations are compared with pretreatment baseline data points and/or photographs. Resource managers oriented to short-range problem-solving, and to the often rapid, easily visible results of other approaches, may consider a biocontrol program less than successful. Questions may even arise as to whether the observed demise of the target species, was, in fact, caused by the biocontrol agent(s), or whether the population reduction would have occurred anyway. Comparison with unaffected populations of the alien species may be difficult if the agent has become well-distributed. Similarly, while some programs have resulted in almost complete elimination of populations of forest weeds (e.g., control of Hamakua pamakani with the smut fungus *Entyloma* sp. (Trujillo 1985, Trujillo et al. 1988) (Figures 1-4), aided by the plume moth *Oidaematophorus beneficus* and the gall fly *Procecidochares alani* at higher elevations in Hawaii (P.-Y. Lai, pers. comm.), researchers may consider a program successful if the population of the target organism is only reduced and held in check, allowing native species to compete. These results, on the other hand, may not be satisfactory to resource managers.

Conflicts of Interest

Biocontrol may not be compatible with other control approaches, such as the obviously detrimental use of certain insecticides to control insect pests for which biocontrol insects have also been introduced. Herbicides may likewise be inhibitive to insects also introduced to control a weed. Selection of chemical pesticides that are not harmful to the specific insects in use is often possible.

Biocontrol agents, once released, may be expected to distribute themselves throughout their biological range without regard to political boundaries or management units. This approach therefore may be inappropriate in areas where varying management strategies are called for. A target plant may be one that has escaped cultivation and invades natural systems, but is desirable as a crop or an ornamental on neighboring land. Kahili ginger (*Hedychium gardnerianum*) in Hawaii is a serious weed capable of invading undisturbed native rain forests. However, this ornamental is prized by the visitor industry for its showy, fragrant flowers and is therefore not a practical candidate for biocontrol at present. Other invading alien species may be closely related to desirable plants such that concern arises over the ability of biocontrol agents to attack the desirable relative, particularly when the supply of the target species becomes limited.

Sugar cane (*Saccharum officinarum*), Hawaii's most important crop, is classified in the same tribe of the Gramineae as is the genus *Andropogon*, two species of which, *A. virginicus* and *A. glomeratus*, are serious invasive weeds in Hawaiian parks, forming dense, monotypic stands which represent an unnatural fire hazard. Importation of biocontrol agents for *Andropogon* spp. may be difficult because of actual or perceived threats to the sugar industry. A significant number of invasive plants in natural systems cannot be considered for biocontrol, at least at present, because of such conflicts of interest.

Conversely, the indigenous shrub a'ali'i (*Dodonaea viscosa*) is protected as a native species in Hawaiian parks, but is sometimes considered an undesirable colonizer of rangeland in nonpark areas. Biocontrol research for this species is therefore not presently under consideration. Since such conflicts of interest lie outside the purview of strictly biological considerations, selection of candidate species for biocontrol must involve public relations efforts by administrators and managers authorized to discuss matters of NPS policy with their counterparts representing the surrounding community.

Biocontrol research throughout the United States has traditionally been conducted by state and federal departments of agriculture, or university scientists who have been free to pursue agricultural priorities without conflict. Entrance of other agencies, such as the NPS, into this field of research presents new issues that must be addressed. Objectives and priorities among agencies conducting biocontrol research may be at cross purposes with one another. The possibility that independent introductions by one agency may cancel the beneficial effects of another introduction must be considered. Koa haole, or leucaena (*Leucaena leucocephala*), an invasive, weedy tree in Hawaii, is a menace to National Park System areas. The accidental arrival in recent years of a psyllid (*Heteropsylla cubana*) which has a controlling effect on this species was welcomed by NPS resource managers as a positive development. However, the Hawaii Department of Agriculture undertook a biocontrol program against this insect since leucaena is used to some extent as cattle fodder and for erosion control (Funasaki et al. 1990).

Ice plant (*Carpobrotus edulis* (= *Mesembryanthemum edule*)), also known as Hottentot fig, an introduction to California from South Africa, is an invading alien species for which control is desired at Point Reyes National Seashore (PORE). A scale insect (*Pulvinariella mesembryanthemi*) is an effective biocontrol agent for this plant. However, Caltrans, the state transportation agency, is actively working to suppress the spread of this insect since it is destroying ornamental plantings of ice plant along freeways (PORE, unpubl. Exotic Plant Management Plan, 1988 draft).

Beekeepers in Florida and Hawaii have expressed opposition to attempts by land-managing agencies to initiate biocontrol programs against either *S. terebinthifolius* or *M. quinquenervia*, as these species are valued for honey production. Nectar-collecting activities of honey bees, however, pollinate paperbark flowers and thereby aid in seed production and consequent spread of the tree (Balciunas and Center 1989).

Agencies involved in biocontrol work, as with other activities, must seek to maintain open avenues of communication and mutually cooperative attitudes. Priorities for research and management can thereby be addressed, which will minimize the development of unproductive bureaucratic protectionism that could inhibit the efficiency of all biocontrol efforts. The NPS Washington Office Division of Wildlife and Vegetation participates as a member of the Technical Advisory Group (TAG) on the Introduction of Biological Control of Weeds, chaired by the United States Department of Agriculture - Animal and Plant Health Inspection Service. Proposals for release of biocontrol agents are reviewed by TAG members representing various interests to determine if conflicts of interest are inherent in such releases. A current issue is the USDA proposal to release insects for control of the native seepwillow (*Baccharis salicifolia*). The National Park Service is expressing opposition to this proposal on the grounds that this action would be in direct conflict with the mission of the National Park Service which is to preserve native species (Technical Advisory Group, unpubl. corres.). On the other hand, USDA entomologists have addressed the problem of possible impacts of biocontrol efforts against leafy spurge (*Euphorbia escula*), a widespread rangeland weed in North America, on sympatric native spurges (Pemberton 1985).

Interagency and International Cooperation

As previously discussed, a full-scale biocontrol program is not confined within park boundaries, but requires cooperation among various state and federal agencies and with scientific and administrative personnel of foreign countries where exploration takes place. Political unrest or negative attitudes toward the United States in certain countries may prevent or limit access by American researchers. Such a situation currently exists in Colombia, where exploration for biocontrol agents for the banana poka vine has been curtailed, disrupting an ongoing research program. Banana poka aggressively colonizes Hawaiian forests, overlaying native vegetation with mats of foliage in much the same manner as does the introduced kudzu vine (*Pueraria lobata*) in the southeastern United States. A second example is fountaingrass (*Pennisetum setaceum*) in Hawaii, a bunchgrass introduced as an ornamental that is aggressively invading drier HAVO regions. Fountaingrass is native to northern Africa, particularly Libya, where travel is not permitted for Americans at this time.

Foreign Travel and Exploration

Due to the necessity of foreign exploration, a biocontrol program is likely to incur significant expenses for foreign travel and exploration, in addition to the cost of constructing and operating a quarantine facility.

Agency administrators must recognize foreign travel as a legitimate and vital function of biocontrol programs. Current NPS foreign travel policy requires that each travel proposal be thoroughly justified on an individual basis by supporting documentation which is reviewed and endorsed at the regional, agency, and departmental levels. This policy is based on the premise that foreign travel is an exceptional activity to be undertaken relatively rarely by NPS employees. The permitting procedure requires considerable time not only of the reviewing officials, but also of the traveler who must prepare the proposal. Furthermore, the permitting procedure is oriented toward representation of the National Park Service at professional meetings or conferences abroad on rigid, preestablished schedules. Experience has shown that while requests for biocontrol exploration have been eventually granted, the review process is cumbersome and has usually required a number of months for completion. Uncertainties during this time interfere with planning and establishing cooperative working commitments with personnel in the countries to be visited.

Foreign travel arrangements for biocontrol purposes should be sufficiently accommodating to allow the researcher discretionary "last minute" flexibility to such local variables as optimal seasonal collecting periods, which may vary from year to year. Official "freezes" directed at curtailing excessive travel are politically expedient, but may result in loss of a year's time to a research program dependent on travel to coincide with a seasonal collection period. If conflicting intraagency purposes are to be avoided, it is vital that travel, domestic as well as foreign, be responsive to the biological needs of the program.

Host Testing

Not only is the selection of target weeds for biocontrol a matter of community concern, choosing appropriate species for host-range testing also ideally involves input from various interests. Host-range testing should include in general native species, crops, and ornamentals either closely related to the target species or of such importance that their omission from testing would not be acceptable from a political standpoint. In Hawaii, due to the economic importance of sugar cane and pineapple, potential biocontrol agents are usually tested on these crops even though this effort would not be justifiable strictly from a biological standpoint.

Thoroughly testing a candidate biocontrol agent under environmental conditions that approximate as nearly as possible those to be encountered in the natural system, while at the same time maintaining security to prevent premature escape, may present considerable tactical problems. Fungi or insects which colonize or feed on leaves may be relatively easily tested by exposing them to detached leaves to determine their ability to infect or use the plant as a food source. However, other host-testing procedures are not as straightforward. Some insects and disease organisms require an intimate association with internal tissues of the host to complete their life cycles, and must be evaluated over extended developmental periods. During such incubation periods, test plants must be capable of surviving under conditions of the quarantine and must be maintained in good, vigorous condition such that effects of the treatment itself can be distinguished.

As an example, a rust fungus, *Gymnoconia nitens*, is currently under evaluation for control of an alien species of bramble, prickly Florida blackberrry (*Rubus argutus*), in Hawaii. Two endemic species of *Rubus* occur in Hawaii as well and must be protected. The fungus is native to the Southeast, where it typically infects the host plant through leaf tissue. However, the leaves remain symptomless during the season in which infection occurs as the fungus extends internally through the stem tissue into the roots, where it overwinters. The fungus then develops internally in new shoots arising from infected roots the following spring, producing severe disease symptoms in the new growth. Manipulation of the natural overwintering requirement may be possible by artificially exposing inoculated plants to cold temperatures for periods shorter than a normal winter season and returning plants to warm conditions for stimulation of regrowth.

Bramble plants from the Hawaiian population were transported to the Southeast where they were inoculated, allowed to overwinter or were artificially exposed to cold temperatures, and produced disease symptoms the following spring (D. E. Gardner, unpubl.). The question remains, however, whether climatic conditions in the regions of Hawaii where control is desired would allow the fungus to complete its natural overwintering cycle and thus serve as an effective control agent. Field testing in Hawaii would provide the most direct information, but this approach would require release of the fungus from quarantine. The native Hawaiian species of *Rubus*, closely related to one another, both occur in high elevation forests and are difficult to grow at the lower elevations where testing has been attempted. Further testing on the U. S. Mainland will be necessary in a location where all plant species in question are suited to the environment, and where the fungus already occurs. Locating a suitable site and making arrangements for such a study illustrate the interorganizational cooperative nature of biocontrol work.

The effects of wood-feeding insects or fungi, such as *Nectria* and *Cryphonectria* which attack the cambium of sizable trees, eventually girdling the trunk, may be accurately evaluated only over extended periods of observation. Likewise, vascular wilt fungi, which are often virulent plant pathogens, typically invade plant roots from the soil and become distributed systemically throughout the vascular system of the plant, causing permanent wilting. While offering promise as biocontrol agents, testing these organisms presents tactical challenges not encountered with simple foliar infection or feeding trials.

If it is desirable, or required as a condition of the permit, that foreign pathogens be host tested at the containment facility at Ft. Detrick, Maryland, the plants to be evaluated, presumably native species as well as crops and ornamentals from the region where the biocontrol agent is to be released, must be transported to Ft. Detrick, either as seeds, cuttings, or seedlings or saplings. If perishable plant material is to be transported long distances, care must be taken that the material is prepared to maintain freshness during shipping, moved to its destination as efficiently as possible (hand carrying is usually preferable), and promptly placed under favorable growing conditions to avoid costly losses caused by undue delays. Some state regulations prohibit movement of soil, which may contain nematodes and other harmful organisms, necessitating the use of artificial rooting medium if intact plants are transported.

Long-Range Prospects for Threatened Ecosystems

The goal of a successful biocontrol program is to provide permanent control without repeated labor intensive efforts (DeBach 1964). Long-range costs are therefore much reduced or negligible. An accompanying benefit is that work crews, sometimes with cumbersome equipment, do not have to enter environmentally sensitive natural areas.

An ironic result of a successful weed control program in which areas are cleared of an alien species may be the appearance of challenges not previously apparent. The question often arises that if resource managers are successful in eliminating or significantly reducing a particular dominating alien species in the environment, what will replace it? Will the newly available habitat be colonized by native species, or will other alien species, perhaps even less desirable than the first, encroach? This question is especially crucial for national parks and other natural areas in island ecosystems, such as those of Hawaii, in which native vegetation types are vulnerable to invasion. Insular systems evolved in isolation from aggressive disturbing influences, but with the relatively sudden introduction of large numbers of alien species as a result of Western colonization, the integrity of these habitats is now severely challenged. Carlquist (1974) stated:

> In the Hawaiian Islands, almost any introduced continental species of plant seems capable of replacing autochthonous species of comparable ecological requirements. ...native island species (with some exceptions) show poorer self-replacement after disturbance than do native species of a comparably disturbed continental area. The rain forests of Kauai now host a remarkable variety of weeds, including many garden flowers, few of which would be noxious - if they were weedy at all - in continental areas. Even high bogs are not exempt from weeds (*Rubus* is now covering the bogs of Mt. Kaala, Oahu). This situation augurs poorly for attempts at conservation of island endemics. Not only are weeds well-entrenched in many areas of the Hawaiian Islands, but efforts to remove them would very likely only renew and widen the areas of disturbance and encourage more weedy growth than before. Many plants that are now weeds in the Hawaiian Islands can hardly be kept out of many areas because of their good dispersal mechanisms. Among the Hawaiian endemics that seem capable of occupying disturbed sites are species of *Scaevola*, *Pipturus*, and *Acacia*. Even with these, one could name more aggressive continental species of comparable ecological requirements.

Trujillo and Obrero (1976) noted that, whereas an invading population of *Cassia surattensis* was dramatically reduced on ranchland by a wilt-inducing isolate of the pathogenic fungus *Cephalosporium* sp., this alien species was replaced by lantana and other weeds as undesirable as was the *Cassia*.

Kikuyugrass, native to Africa, was imported to Hawaii as a pasture species. Unfortunately, this grass has also exhibited the ability to spread aggressively into native forests from roadsides and other disturbed areas. Resource managers may successfully employ biocontrol in eliminating or reducing ground-covering species such as Hamakua pamakani, but kikuyugrass shows the ability to quickly recolonize cleared areas. Biocontrol is not currently feasible due to the value of kikuyugrass elsewhere as a pasture species.

As a further example of the uncertainties of long-range vegetation management, feral goats, purposefully released in the Hawaiian Islands by early European explorers, had attained such explosive population levels by the 1900s that vast expanses of mesic National Park System land had become severely overgrazed, exposing bare soil to the effects of erosion. Massive control efforts, widely recognized for their dramatic success, have shown great promise in leading to the virtual elimination of goat populations on National Park System lands. However, with the release from grazing pressure, formerly goat-occupied habitat in the lowlands has

become colonized by molassesgrass (*Melinis minutiflora*) and other alien grasses which themselves create unnatural fire hazards and interfere with succession by native species. Biocontrol measures against the grasses are under consideration. The suggestion has been made that perhaps goats should be reintroduced as the most effective biocontrol agents. Although not usually intended as a serious proposal, this statement does illustrate the dilemmas encountered in the overall, long-range management of severely threatened native systems, not only with reference to alien species but in other aspects as well, in which conflicting management policies appear to have merit. These examples illustrate the need for comprehensive, long-term scientific investigations designed to gain as complete an understanding as possible of the overall ramifications of perturbations in native environments, and those of the possible alleviating measures.

Conclusions

Invasion by alien species, and the resulting habitat destruction and displacement of native species, are among the most serious threats to protected natural areas, becoming an extremely critical threat in certain national parks. Control of well-established infestations over large areas requires consideration of all applicable approaches. Biocontrol appears to offer an attractive solution to many of these problems. As previously pointed out, several examples of successful, even dramatic, biocontrol programs are available, which have achieved the desired results with a minimum of negative side effects and at a reasonable cost.

This discussion emphasizes that not all alien species in natural systems are amenable to biocontrol approaches for any of a variety of reasons. Each alien plant or insect problem must be considered individually for possible applicability of biocontrol (Markin et al., in press). While the ability of biocontrol agents to distribute themselves throughout their biological range is an attribute contributing to their effectiveness, this tendency may also lead to conflicts of interest; political boundaries are exceeded. Exploration of native habitats for potential agents may not be feasible due to unstable political situations in the country of origin of the biocontrol agent. Furthermore, host-specific agents able to significantly impact the target species may not be available.

Perhaps the most significant current constraint to successful biocontrol programs is the lack of research facilities and trained personnel available to conduct these studies. This constraint is accompanied by lack of information on many of the animals (principally insects) and pathogens that can be investigated as potential biocontrol agents, as well as the basic biology of the alien species to be controlled. Such information must often be gained through direct exploration in the native habitat of the introduced species, followed by experimentation in the native habitat and/or under quarantine conditions in the location of intended release. Most biocontrol work conducted by agencies such as the National Park Service has been opportunistic, relying on initial research performed by agricultural agencies for pests also of concern in natural areas. Agencies that manage natural areas have yet to become fully involved in initiating and pursuing biocontrol research to directly address their problems. Such involvement requires specialized equipment (including quarantine facilities) and well-trained scientists. This, in turn, requires a significant long-term commitment on the part of the managing agency, supported by sufficient funding for an expensive program. On the other hand, as exploration continues and successful combinations of target species and controlling agents are found, and the long-range cost-effectiveness of such programs is realized, more impetus will undoubtedly be given biocontrol programs as management tools in natural areas.

Many examples of successful control of individual alien species through biological approaches are available. However, the overall prospect of restoring native systems themselves to their pristine conditions presents a much greater challenge to resource managers of island ecosystems and other areas where native species are vulnerable to invasion by alien species (Carlquist 1974).

Management and Administrative Considerations

Invading alien species threaten the integrity of natural resources throughout the National Park System. These threats are particularly severe in parks situated in tropical and subtropical areas. NPS pesticide use guidelines call for the consideration of: (1) no action, (2) mechanical and cultural control, and (3) biocontrol in preference to the use of chemical pesticides to combat these threats. In practice, however, these guidelines are often not followed because of the accessibility and ease of application of chemicals that yield positive, immediate results. On the other hand, the facilities, expertise, funding, and time required to explore first the potential of biocontrol are usually not available to resource managers.

The National Park Service and other agencies charged with the management of protected natural areas have management needs not directly addressed by agricultural agencies, where most biocontrol work is currently being undertaken. In accordance with established guidelines for alien species control, the National Park Service should move from a secondary or passive position with regard to biocontrol activities and become more actively and directly involved in independent biocontrol research designed to address the particular, frequently noneconomic, needs of natural environments.

The NPS biocontrol quarantine facility at Hawaii Volcanoes National Park serves as a general prototype for the remainder of the Service. A comprehensive, National Park Systemwide assessment of alien species control requirements should be made. This assessment would enable NPS administrators to determine the number, locations, specifications, and staffing requirements of biocontrol research laboratories capable of meeting NPS needs. Such a system should be established on a coordinated multipark or multiregional basis, such that duplication of effort among parks and regions with similar problems is avoided, and biological needs be given primary concern rather than intraagency administrative jurisdictions.

Foreign travel and cooperative efforts with foreign countries should be recognized as essential components of biocontrol research. Travel policies and procedures should be updated to support the need for frequent and flexible travel necessary to conduct exploration for biocontrol agents, and to establish cooperative working agreements with scientists and resource managers in countries of origin of alien species.

The potential for biocontrol involvement should be a prominent consideration in any IPM program undertaken by the National Park Service and similar managing agencies of protected natural areas. The IPM concept implies consideration of all possible approaches and combinations of approaches to a pest problem. In practice, the possibility of biocontrol is sometimes overlooked as a component of IPM programs.

Through its continued participation in the Technical Advisory Group on the Introduction of Biological Control of Weeds, the National Park Service should readily exercise judgment of, and express strong opposition to, biocontrol programs undertaken by other agencies directed against native species or which may otherwise negatively impact park resources or objectives. Whereas agricultural concerns have heretofore been exclusively represented and have received primary recognition in biocontrol programs, the National Park Service should assert itself as an agency with serious concerns in this area as well.

With several well-known exceptions, such as the gypsy moth, invading alien organisms in natural areas of greatest present concern in the National Park System are weeds rather than insects. This emphasis may be to some extent a result of the frequently more visible presence of plant infestations than those of insects. However, research in some parks is indicating that depredations resulting from colonization of native habitat by alien insects may also be exerting a formerly little-recognized negative impact. Higher priority for entomological research from an ecological standpoint is recommended to more fully assess the extent of this threat. Likewise, whereas lists of alien species are available in most parks, the actual ecological impact of invading species in native environments should be comprehensively documented in support of biocontrol programs. The National Park Service and similar agencies should encourage and sponsor research directed at this objective.

Although elimination or control of particular alien species may be feasible through biocontrol approaches, resource managers should be aware that in tropical and subtropical areas, and in insular systems in particular, where numerous aggressive alien species occur, the innate lack of competitive ability among endemic species may be a limiting factor in attempts to restore native systems themselves to their intact, pristine conditions.

Literature Cited

Anonymous. 1981. Biological control of Klamath weed in Yosemite NP. Park Science 2(1):10.

Balciunas, J., and T. D. Center. 1989. Searching for *Melaleuca quinquenervia* (broad-leaved paperbark) herbivores in Australia. Interim Report Submitted to the United States Army Engineers District, Jacksonville, Florida, and the National Park Service. 19 pp.

Barreto, R. W., and H. C. Evans. 1988. Taxonomy of a fungus introduced into Hawaii for biological control of *Ageratina riparia* (Eupatorieae; Compositae), with observations on related weed pathogens. Transactions of the British Mycological Society 91:81-97.

Bowers, R. C. 1982. Commercialization of microbial biological control agents. Pages 157-173 in R. Charudattan and H. L. Walker, eds..Biological control of weeds with plant pathogens. John Wiley & Sons, New York.

Boyette, C. D., G. E. Templeton, and L. R. Oliver. 1984. Texas gourd (*Cucurbita texana*) control with *Fusarium solani* f. sp. *cucurbitae*. Weed Science 32:649-655.

Carlquist, S. 1974. Island biology. Columbia University Press, New York.

Carpenter, C. W. 1944. *Fusarium* disease of the prickly pear. Hawaiian Planters' Record 48:59-63.

Charudattan, R. 1982. Regulation of microbial weed control agents. Pages 175-188 in R. Charudattan and H. L. Walker, eds. Biological control of weeds with plant pathogens. John Wiley & Sons, New York.

Charudattan, R., and H. L. Walker, eds. 1982. Biological control of weeds with plant pathogens. John Wiley & Sons, New York.

Cullen, J. M., P. F. Kable, and M. Catt. 1973. Epidemic spread of a rust imported for biological control. Nature 244:462-464.

Daniel, J. T., G. E. Templeton, R. J. Smith, Jr., and W. T. Fox. 1973. Biological control of northern jointvetch in rice with an endemic fungal disease. Weed Science 21:303-307.

Davis, C. J., E. Yoshioka, and D. Kageler. Biological control of lantana, prickly pear, and Hamakua pamakani in Hawaii: a review and update. In C. P. Stone, C. W. Smith, and J. T. Tunison, (eds.). Alien plant invasions in native ecosystems of Hawaii: management and research. University of Hawaii Press, Honolulu. (in press).

DeBach, P. 1964. Biological control of insect pests and weeds. Reinhold Publication Corporation, New York.

Doren, R. F. 1989. Exotic or alien - either defines "pest." Park Science 9(3):5.

Emge, R. G., J. S. Melching, and C. H. Kingsolver. 1981. Epidemiology of *Puccinia chondrillina*, a rust pathogen for the biological control of rush skeleton weed in the United States. Phytopathology 71:839-843.

Fullaway, D. T. 1954. Biological control of cactus in Hawaii. Journal of Economic Entomology 47:696-700.

Funasaki, G. Y., P.-Y. Lai, and L. M. Nakahara. 1990. Status of natural enemies of *Heteropsylla cubana* Crawford (Homoptera:Psyllidae) in Hawaii. Pages 153-158 in B. Napompeth and K. G. MacDicken, eds. Leucaena psyllid: problems and management. Proceedings of International Workshop January 16-21, 1989; Bogor, Indonesia.

Funasaki, G. Y., P.-Y. Lai, L. M. Nakahara, J. W. Beardsley, and A. K. Ota. 1988. Review of Biological control introductions in Hawaii: 1890-1985. Proceedings of the Hawaiian Entomological Society 28:105-160.

Gambino, P., A. C. Medeiros, and L. L. Loope. 1987. Introduced *Paravespula pensylvanica* (Saussure) yellowjackets prey on Maui's endemic arthropod fauna. Journal of Tropical Ecology 3:169-170.

Gardner, D. E. 1982. Exotic plants in Hawaii's national parks: a major challenge. Park Science 2(2):18-19.

Gardner, D. E. 1984. Kikuyugrass rust caused by *Phakopsora apoda* in Hawaii. Plant Disease 68:826.

Gardner, D. E. Plant pathogens as biocontrol agents in native Hawaiian ecosystems. In C. P. Stone, C. W. Smith, and J. T. Tunison, eds. Alien plant invasions in native ecosystems of Hawaii: management and research. University of Hawaii Press. (in press).

Gardner, D. E., and C. J. Davis. 1982. The prospects for biological control of nonnative plants in Hawaiian national parks. University of Hawaii Cooperative National Park Studies Unit Technical Report 45. University of Hawaii, Honolulu.

Gardner, D. E., G. P. Markin, and C. S. Hodges, Jr. 1988. Survey for potential biological control agents for *Myrica faya* in the Azores and Madeira. University of Hawaii Cooperative National Park Studies Unit Technical Report 63. University of Hawaii, Honolulu.

Gardner, D. E., and C. W. Smith. 1985. Plant biocontrol quarantine facility at Hawaii Volcanoes. Park Science 6(1):3-4.

Hasan, S. 1972. Specificity and host specialization of *Puccinia chondrillina*. Annals of Applied Biology 72:257-263. Hasan, S., and A. J. Wapshere. 1973. The biology of *Puccinia chondrillina*, a potential biological control agent of skeleton weed. Annals of Applied Biology 74:325-332.

Hodges, C. S., Jr., and D. E. Gardner. 1985. *Myrica faya*: Potential biological control agents. University of Hawaii Cooperative National Park Studies Unit Technical Report 54. University of Hawaii, Honolulu.

Holden, L. J. 1985. Tansy flea beetle wins ragwort sweepstakes at Redwood NP. Park Science 5(4):10-11.

Howarth, F. S. 1983. Classical biocontrol: panacea or Pandora's box? Proceedings of the Hawaiian Entomological Society 24:239-244.

Julien, M. H. 1982. Biological control of weeds. A world catalogue of agents and their target weeds. Commonwealth Institute of Biological Control, Commonwealth Agricultural Bureau, Farnham, Slough, United Kingdom.

Kahn, R. P. 1983. A model plant quarantine station: principles, concepts, and requirements. Pages 303-333 in K. G. Singh, ed. Exotic plant quarantine pests and procedures for introduction of plant materials; Serdang, Selangor, Malaysia: ASEAN Plant Quarantine Centre and Training Institute.

Klingman, D. L., and J. R. Coulson. 1983. Guidelines for introducing foreign organisms into the United States for the biological control of weeds. Bulletin of the Entomological Society of America 29:55-61.

Lai, P.-Y. 1988. Biological control: a positive point of view. Proceedings of the Hawaiian Entomological Society 28:179-190.

Loope, L. L., A. C. Medeiros, and F. R. Cole. 1988. Effects of the Argentine ant on the endemic biota of subalpine shrubland, Haleakala National Park, Hawaii. Pages 52-62 in L. K. Thomas, ed. Management of exotic species in natural communities. Vol. 5. Proceedings of the conference on science in the national parks; July, 1986. Ft. Collins, Colorado. United States National Park Service and The George Wright Society.

Markin, G. P., P.-Y. Lai, and G. Y. Funasaki. Status of biological control of weeds in Hawaii and implications for managing native ecosystems. In C. P. Stone, C. W. Smith, and J. T. Tunison, eds. Alien plant invasions in native ecosystems of Hawaii: management and research. University of Hawaii Press, Honolulu. (in press).

Markin, G. P., and R. F. Nagata. 1989. Host preference and potential climatic range of *Cyanotricha necyria* (Lepidoptera: Dioptidae), potential biological control agent of the weed *Passiflora mollissima* in Hawaiian forests. University of Hawaii Cooperative National Park Studies Unit Technical Report 67. University of Hawaii, Honolulu.

Markin, G. P., and E. Yoshioka. Evaluating proposed biological control programs for introduced plants. In C. P. Stone, C. W. Smith, and J. T. Tunison, eds. Alien plant invasions in native ecosystems of Hawaii: management and research. University of Hawaii Press, Honolulu. (in press).

Melching, J. S., K. R. Bromfield, and C. H. Kingsolver. 1983. The plant pathogen containment facility at Frederick, Maryland. Plant Disease 67:717-722.

Oehrens, E. 1977. Biological control of the blackberry through the introduction of rust, *Phragmidium violaceum*, in Chile. FAO Plant Protection Bulletin 25:26-28.

Pemberton, R.W. 1985. Native plant considerations in the biological control of leafy spurge. Pages 365-390 in E. S. Delfosse, ed. Proceeding of the VI symposium on the biological control of weeds. August 19-25, 1984. Vancouver, Canada. Agriculture Canada.

Piper, G. L. 1985. Biological control of weeds in Washington: status report. Pages 818-826 in E. S. Delfosse, ed. Proceedings of the VI International symposium on the biological control of weeds; August, 1984. Vancouver, Canada. Agriculture Canada.

Reardon, R., and W. Carothers. 1988. Gypsy moth integrated pest management in parks of the National Capital Region. Pages 80-84 in L. K. Thomas, ed. Management of Exotic Species in Natural Communities. Vol. 5. Proceedings of the Conference on Science in The National Parks; July, 1986. Ft. Collins, Colorado. National Park Service and The George Wright Society.

Ryan, R. B. 1987. Classical biological control: an overview. Journal of Forestry 85:29-31.

Ryan, R. B., S. Tunnock, and F. W. Ebel. 1987. The larch casebearer in North America. Journal of Forestry 85:33-39.

Sherald, J. L., and R. S. Hammerschlag. 1982. Science and management work together in controlling Dutch elm disease in NCR. Park Science 2(2):10-11.

Shrum, R. D. 1982. Creating epiphytotics. Pages 113-136 in R. Charudattan and H. L. Walker, eds. Biological control of weeds with plant pathogens. John Wiley & Sons, New York.

Smith, R. J., Jr., J. T. Daniel, W. T. Fox, and G. E. Templeton. 1973. Distribution in Arkansas of a fungus disease used for bio-control of northern jointvetch in rice. Plant Disease Reporter 57:695-697.

TeBeest, D. O. 1984. Biological control of weeds with microbial herbicides. Fitopatologia Brasileira 9:443-453.

Templeton, G. E. 1982. Status of weed control with plant pathogens. Pages 29-44 in R. Charudattan and H. L. Walker, eds. Biological control of weeds with plant pathogens. John Wiley & Sons, New York.

Torgersen, T. R., and A. S. Torgersen. 1990. Saving forests the natural way. American Forests 96:31-33, 46.

Trujillo, E. E. 1985. Biological control of Hamakua pamakani with *Cercosporella* sp. in Hawaii. Pages 661-671 in E. S. Delfosse, ed. Proceeding of the VI symposium on the biological control of weeds. August 19-25, 1984. Vancouver, Canada. Agriculture Canada.

Trujillo, E. E., M. Aragaki, and R. A. Shoemaker. 1988. Infection, disease development, and axenic culture of *Entyloma compositarum*, the cause of Hamakua pamakani blight in Hawaii. Plant Disease 72:255-257.

Trujillo, E. E., F. M. Latterell, and A. E. Rossi. 1986. *Colletotrichum gloeosporioides*, a possible biological control agent for *Clidemia hirta* in Hawaiian forests. Plant Disease 70:974-976.

Trujillo, E. E., and F. P. Obrero. 1976. *Cephalosporium* wilt of *Cassia surattensis* in Hawaii. Pages 217-220 in T. E. Freeman, ed. Proceedings of the IV international symposium on biological control of weeds. University of Florida, Gainsville.

Tunison, J. T., and C. P. Stone. The special ecological area approach to alien plant control in Hawaii Volcanoes National Park. In C. P. Stone, C. W. Smith, and J. T. Tunison, eds. Alien plant invasions in native ecosystems of Hawaii: management and research. University of Hawaii Press, Honolulu. (in press).

Tunison, J. T., C. P. Stone, and L. W. Cuddihy. 1986. SEAs provide ecosystem focus for management and research. Park Science 6(3):10-13.

United States Department of Agriculture. 1978. Biological agents for pest control. Status and prospects. United States Government Printing Office, Washington, D.C.

van den Bosh, R., P. S. Messenger, and A. P. Gutierrez. 1982. An introduction to biological control. Plenum Press, New York.

Wagner, M. 1986. Give us park rangers to match our grasshoppers. Park Science 6(2):17.

Wapshere, A. J. 1975. A protocol for programmes for biological control of weeds. Pest Article News Summary (PANS) 21:295-303.

Weidemann, G. J., and G. E. Templeton. 1988. Efficacy and soil persistence of *Fusarium solani* f. sp. *cucurbitae* for control of Texas gourd (*Cucurbita texana*). Plant Disease 72:36-38.

Wilson, C. L. 1969. Use of plant pathogens in weed control. Annual Review of Phytopathology 7:411-434.

Zettler, F. W., and T. E. Freeman. 1972. Plant pathogens as biocontrols of aquatic weeds. Annual Review of Phytopathology 10:455-470.

Zimmerman, E. C. 1958. Insects of Hawaii. Vol. 7 (Macrolepidoptera). University of Hawaii Press, Honolulu.

Zwoelfer, H., M. A. Ghani, and V. P. Rao. 1976. Foreign exploration and importation of natural enemies. Pages 198-207 in C. B. Huffaker and P. S. Messenger, eds. Theory and practice of biological control. Academic Press, London.

☆U.S. GOVERNMENT PRINTING OFFICE: 1990-776-899/25177

As the nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural and cultural resources. This includes fostering wise use of our land and water resources, protecting our fish and wildlife, preserving the environmental and cultural values of our national parks and historical places, and providing for enjoyment of life through outdoor recreation. The department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people. The department also promotes the goals of the Take Pride in America campaign by encouraging stewardship and citizen responsibility for the public lands and promoting citizen participation in their care. The department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

NPS D-549 September 1990